Identification of geomagnetic pulsations in SQUID data for Space Weather research

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Abstract*—An HTS (High Temperature Superconductor) SQUID magnetometer is located at the INTERMAGNET Hermanus Magnetic Observatory (HER) site in South Africa. The LN_2-cooled SQUID is operated unshielded and records the geomagnetic field continuously. If validated, the SQUID may be used as a space weather instrument. The SQUID records small geomagnetic variations such as pulsations, which are short period fluctuations of the geomagnetic field at ULF frequencies. Although the SQUID magnetometers are about 10× more sensitive than fluxgate magnetometers, it is running in an urban environment contaminated by anthropogenous noise. It was also found that one of the SQUIDs is prone to thermally induced oscillations due to thermos-acoustic oscillations in the dewar. To distinguish pulsations from uncorrelated noise, the SQUID data is correlated with fluxgate data from the two closest INTERMAGNET observatories, Hartebeesthoek (HBK) and Keetmanshoop (KMH), both located more than 1000 km away. Man-made noise and SQUID oscillations should give low coherence between SQUID/KMH and SQUID/HBK pairs. Coherence higher than 0.9 was found when pulsations were present in the data and the algorithm has also proven effective on data contaminated with the thermal SQUID oscillations.

***Index Terms*—Geomagnetic field, pulsations, space weather, SQUID, thermal oscillations**

I. INTRODUCTION

An HTS (High Temperature Superconductor) SQUID magnetometer is located at the Hermanus Magnetic Observatory (HER) in South Africa and has been in operation for the past 13 years, with near continuous operation (95%) during the past 3 years. The LN_2-cooled SQUID is operated unshielded and records the three components of the geomagnetic field continuously [1], including small geomagnetic variations such as pulsations.

The HER observatory in South Africa also boasts a 24/7 space weather prediction centre, and it is with this application in mind that the SQUID is investigated as a space weather instrument, which is a novel application for SQUIDs - similar studies in remote locations were done with He-cooled, shielded, Low Temperature SQUIDs [2][3] but were not aimed for a long-term operation as a geophysical instrument.

The utilized SQUID magnetometer is co-located with observatory grade fluxgate magnetometers which validate the SQUID data. The SQUID magnetometer is an order of magnitude more sensitive than the fluxgate magnetometers, but operates in a semi-urban environment where it suffers from anthropogenous noise. The monitoring of geomagnetic pulsations using the SQUID magnetometer would be an excellent space weather application, however, the surrounding anthropogenous noise often falls within the same frequency range as the geomagnetic events, mainly for sub-nanotesla magnitudes. This paper investigates the possibility of identifying the SQUID recorded pulsations in the presence of anthropogenous noise by correlating the data with magnetic observatories some distance away, where the anthropogenous noise will not be correlated to the SQUID.

We show that the most sensitive SQUID magnetometer suffers from thermal noise due to an apparent high temperature coefficient of the instrument, coupled to thermal oscillations in the LN_2 bath. The frequency of these oscillations is unfortunately close to that of the geomagnetic pulsations under investigation, creating a significant challenge. The oscillation effect is presented as well as an algorithm for coherence calculations, which was shown as effective to mitigate this parasitic effect, allowing us to use the full SQUID data, not only the “quiet days” i.e. around one day before and after dewar refill.

II. BACKGROUND

A. Geomagnetic Pulsations

Geomagnetic pulsations are small fluctuations of the near-Earth magnetic field typically falling within the ultra-low frequency (ULF) range between about 1 mHz to 1 Hz [4][5][6]. ULF pulsations can be driven by various types of mechanisms in the magnetosphere and the upstream solar wind. The nature of the plasma instabilities and the efficiency of coupling with different plasma populations and their transfer to the inner magnetosphere and ionosphere is dependent on prevailing conditions in the solar wind and magnetosphere. ULF waves

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show oscillations with a quasi-sinusoidal waveform (Pc) or irregular waveforms (Pi), which are further divided into period bands that isolate a specific type of pulsation. The geomagnetic pulsations most commonly observed at low to middle latitudes during local daytime are Pc3 (22-100 mHz) and Pc4 (7-22 mHz) quasi-sinusoidal continuous pulsations [5] with amplitudes of up to a few nT. Pc3 and Pc4 waves are routinely caused by waves in the upstream solar wind propagating into the magnetosphere where wave power is transferred to the ionosphere. The ULF wave signals detected at ground level provide information about the region it has propagated through, rather than from the region (magnetosphere) it was generated.

Historically the spectral structure of Pi, Pc3 and Pc4 ULF pulsations [7][8], has been studied using low latitude ground-based stations in South Africa, which usually consisted of 1 Hz induction magnetometer data. These have been replaced in 2013 by LEMI-025 fluxgate magnetometers [9].

Geomagnetic storms are multi-day events characterized by the impact and subsequent disturbance of the geomagnetic field by fast, dense solar wind plasma, typically originating from coronal mass ejections (CME) [10]. The disturbance of the geomagnetic field can cause various negative impacts on technological systems on the Earth and in space [11]. Geomagnetic pulsations can serve to indicate the current state of the magnetosphere during the onset, expansion and recovery phases of a geomagnetic storm, as different types of wave-particle interactions are indicative of different coupling and recovery processes. Pulsation events are heavily affected by any change in orientation of the interplanetary magnetic field or an increase in solar wind velocity [5][12]. Pi2 pulsations occur during magnetospheric substorm onsets and intensifications [13] in mid- or low latitudes on the nightside [14], which makes it a good indicator of substorms [15] and an important tool in space weather monitoring and forecasting [9][11]. The high fidelity of SQUID observations would enable increased sensitivity and time resolution of Pc and Pi pulsation events.

B. SQUID setup at the observatory site

The 3-axis HTS SQUID magnetometer has an M2700 SQUID from Star Cryoelectronics ($25\ \mathrm{nT}/\phi_0$, $<300\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$) as vertical axis and both horizontal axes are HTM-8 SQUIDs from FZ Jülich ($4.5\ \mathrm{nT}/\phi_0$, $<45\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$). The SQUID magnetometer is LN$_2$-cooled in a 34-litre unpressurised dewar and operated unshielded. The LN2 dewar is manually refilled every 3.5 weeks due to the high boil-off rate, limited by the selected dewar and losses due to the SQUID installation. The SQUID magnetometer is located in a non-magnetic building and co-located (2 m) with a low noise 3-axes fluxgate magnetometer from the Czech Technical University, as well as the HER observatory DMI FGE [16] fluxgate magnetometer (70 m); both used as references for the SQUID that is a relative instrument [17]. The SQUID magnetometer is generally 10× more sensitive to changes in the magnetic flux density than the reference fluxgate magnetometers.

The 16 ha HER magnetic observatory site [18], where the SQUID is located, is magnetically clean to INTERMAGNET standards. However, it is located in a semi-urban environment where it is surrounded by a general residential area, 3 hospitals, a light industrial area, and located 400 m from the Atlantic Ocean. These factors add to the increased anthropogenous noise present.

The final purpose of the SQUID magnetometer would be as an additional space weather instrument to add sensitivity and higher temporal resolution to space weather measurements [1].

III. THERMAL OSCILLATIONS IN THE DEWAR

During installation of the horizontal HTM-8 SQUIDs it was observed that these SQUIDs exhibit excess noise as a low frequency oscillation up to $2\ \mathrm{nT}_{pp}$, $T \approx 200$ s or $f \approx 5\text{-}6$ mHz. Unfortunately, this falls well within the frequency range of geomagnetic pulsations, which are the subject of this study, and may be too close to Pc pulsation frequencies for unique correlation results.

All sources of oscillations were investigated, including monitoring during an unrelated complete absence of electricity grid supply at the site and surrounding town; the observed oscillations persisted. A non-magnetic resistive temperature sensor was inserted in the LN$_2$ bath, and $6\ \mathrm{mK}_{pp}$ temperature oscillations were recorded at 5-6 mHz [19]. Correlation between the oscillations on the SQUIDs and the temperature oscillations measured implied that $6\ \mathrm{mK}_{pp}$ temperature oscillations yield $2\ \mathrm{nT}_{pp}$ SQUID oscillations (Fig. 1). After additional tests in an alternative dewar of similar shape and volume [19] it was concluded that the temperature oscillation in the LN$_2$ bath is caused by irregular boil off rate [20] and the specific thermal resonance is determined by dewar shape, heat influx and pressure changes.

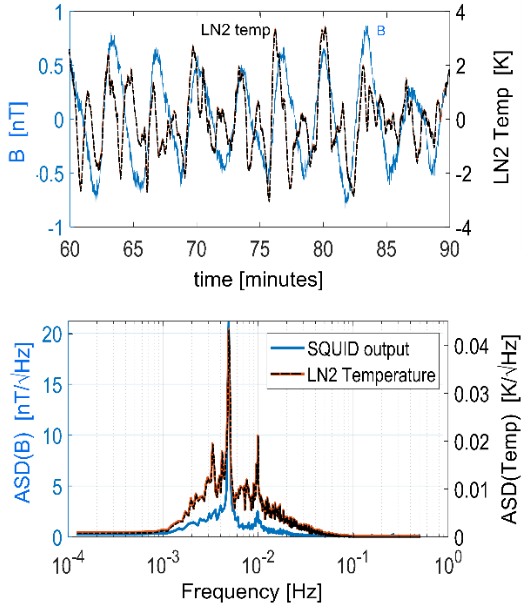

Fig. 1. 5 mHz SQUID and LN$_2$ temperature oscillations, time domain (top) and amplitude spectrum (bottom).

The LN$_2$ dewar is refilled every 3.5 weeks, when the level drops to 42 cm below the neck. The dewar is refilled into the neck to the top completely, so for the first 24 hours after refill the LN$_2$ does not fall below the shoulder of the dewar. Long

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term data has shown that the amplitude and frequency of oscillations changes slightly as the level of the LN_2 decreases, implying that the increasing volume of vapor phase in the dewar plays a role. Fig. 2 shows the change in the 5 mHz oscillations, also showing that the oscillations disappear towards end of LN_2 refill period and 1 day thereafter. Thus, initially the use of horizontal SQUID data for geomagnetic pulsations was limited to these thermally quiet days.

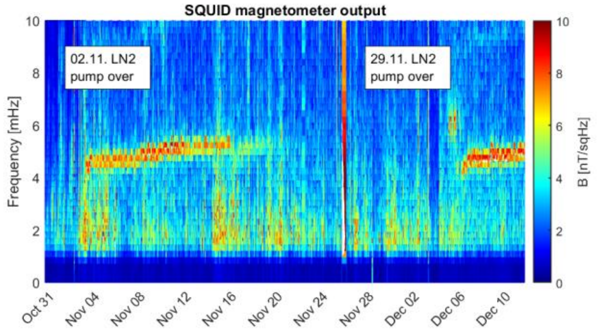

Fig. 2. Frequency spectra of HTM-8 oscillations.

IV. COHERENCE OF MAGNETIC DATA

A. Pulsations vs anthropogenous noise

In order to identify geomagnetic pulsations in SQUID data, it is necessary to distinguish pulsations from anthropogenous noise. Although the SQUID utilizes two on-site fluxgate magnetometers as reference, these magnetometers would suffer from the same or similar man-made noise. Thus, we correlated the SQUID data with fluxgate data from INTERMAGNET magnetic observatories located far away, where anthropogenous noise correlation are not expected. The SQUID data were correlated with fluxgate data from the Hartebeesthoek (HBK) observatory, with 9° difference in both longitude and latitude (1400 km NE), as well as the Keetmanshoop (KMH) observatory 1000 km North of HER. The lower sensitivity and higher noise of HBK and KMH magnetometers do not affect the coherence calculation.

B. SQUID and observatory data processing

The 4 Hz SQUID data is down-sampled using a digital filter to 1 Hz to compare with 1 Hz INTERMAGNET observatory data. The data from both the SQUID and KMH/HBK magnetometers are bandpass filtered between 3 – 250 mHz with a 20th order infinite impulse response (IIR) filter to remove the diurnal geomagnetic field variation and higher frequency signals not of interest. Coherence using the Welch method estimation of the power spectral density (PSD) [21] is computed using MATLAB software and “mscohere” package [22]. Coherence is calculated in a sliding window with 30 or 60 minutes length, 93% overlap, using an FFT of 1024 points. Coherence throughout the day is plotted in a “coherogram”.

C. Coherence in Z: SQUID and HBK

The advantage of the Z-axis (B_z, vertical) SQUID is its immunity to the oscillations in the dewar, so first trials were done using the Z component of the magnetic field. Fig. 3 shows data from 2022-10-04. The difference between the SQUID and HBK data is mainly due to anthropogenous noise in Z at the SQUID location. As depicted in the spectrograph, during the daytime Pc3 pulsations were observed in the SQUID and HBK data sets with coherence higher than 0.9 at 36, 41 and 44 mHz. During night-time Pi pulsations were observed in both data sets with coherence of 0.97 at 12.7 to 22.5 mHz. During the remainder of the 24 hours coherence between the data sets were around 0 with peaks up to 0.17.

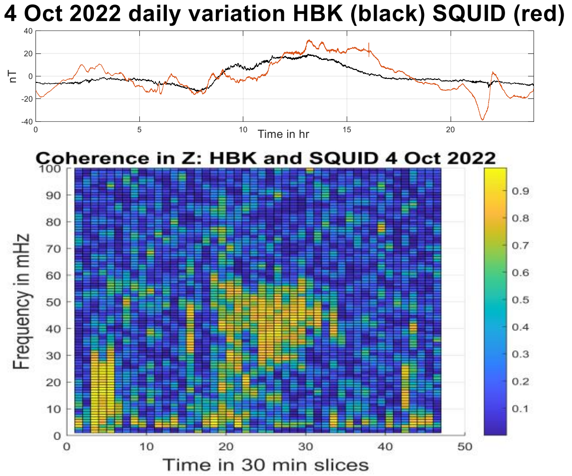

Fig. 3. Time domain and coherence SQUID and HBK: Z axis.

D. Coherence in H: SQUID and KMH, before and after refill

For coherence in the H axis (B_H, local magnetic north) two days with observed pulsations are presented (Fig. 4 and 5), which are oscillation free days 1 day before and after refill.

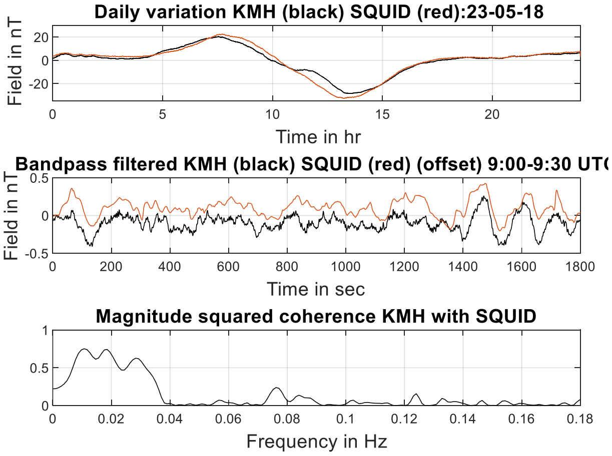

Fig. 4. Raw data, filtered data and coherence in H axis.

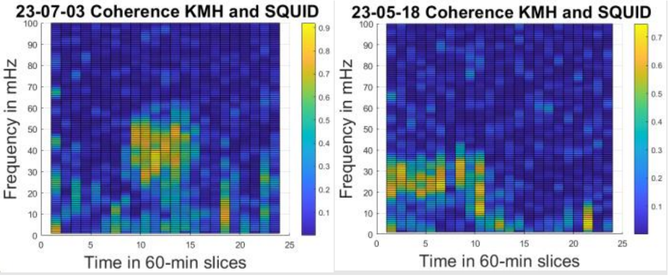

Fig. 5. Coherence in the H axis: SQUID and KMH, 2 days

Pulsations are observed in both KMH and SQUID data both on 2023-05-18 and 2023-07-03 with coherence about 0.62 to 0.93, between 11 - 46 mHz. The time-domain plot in Fig. 4 with pulsation amplitudes ~ 0.1 nT shows the advantage of our method. In the time domain one could not identify anthropogenous noise from pulsations with certainty, especially given that these levels are on the edge of the KMH fluxgate magnetometer resolution, as opposed to the SQUID which has much higher sensitivity.

E. Coherence in H: SQUID and KMH, 3 days before refill

Coherence results in the H axis are shown for 2023-03-04 at 14:00-14:30 UTC; 3 days before refill. Although the 5 mHz oscillations were still present, the amplitude is already low. Fig. 6 shows the bandpassed time-domain data. The pulsations recorded on the SQUID show excellent correlation with both HBK and KMH (Fig. 7). The results, which show almost no coherence at 5 mHz, indicated that this method could be feasible for remaining days with 5 mHz oscillations present.

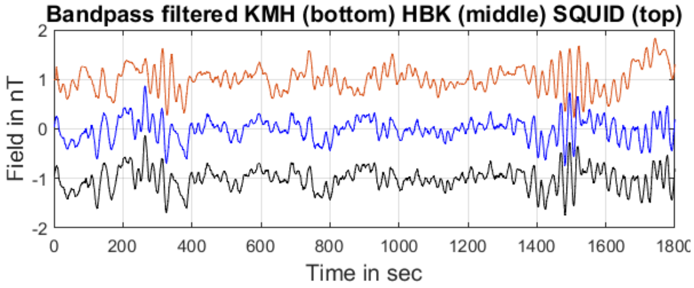

Fig. 6. Bandpass filtered data, ± 1 nT offset for visibility.

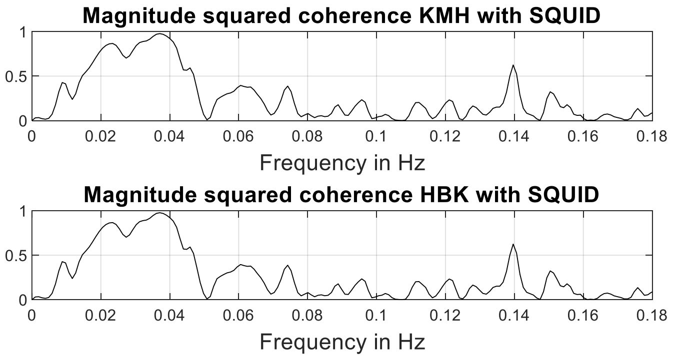

Fig. 7. Coherence with HBK and KMH; low 5 mHz amplitude.

F: Coherence in H: SQUID and KMH, high 5 mHz oscillation

We are showing results for 2023-09-20 with clearly observed pulsations as well as 5 mHz oscillations in the time domain (Fig. 8 and 9). During the first 30 minutes the SQUID data coincides with the KMH data, but during the last 30 minutes the inherent 5 mHz SQUID temperature induced oscillations are evident. The SQUID shows excellent correlation with both HBK and KMH for pulsation frequencies, and with minimal coherence at 5 mHz (theoretically it would be zero).

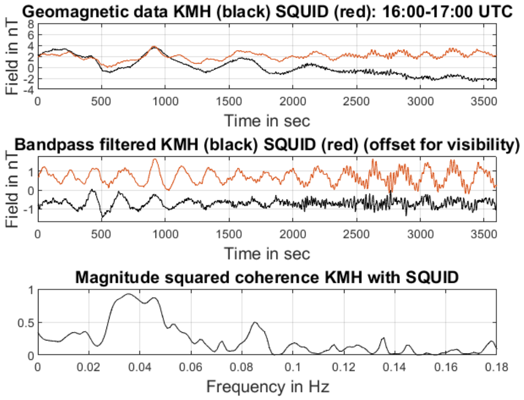

Fig. 8. Coherence with KMH, 5 mHz visible in time domain.

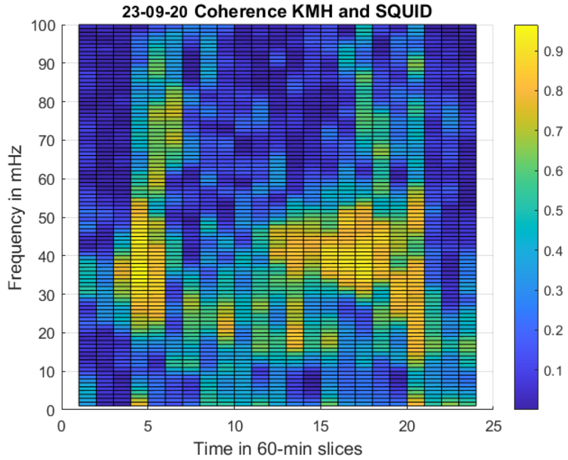

Fig. 9. Coherence SQUID and KMH, 5 mHz not visible.

V. CONCLUSION

Coherence calculations between unshielded SQUID and fluxgate data from magnetic observatories located 1000 – 1500 km away was shown as a useful tool to obtain information on whether we are observing anthropogenous noise or actual geomagnetic signal. We are able to confirm Pc and Pi geomagnetic pulsations both in the vertical and horizontal axes Pulsations even smaller than 0.1 nT in amplitude were successfully detected, which would not be possible with a single observatory fluxgate magnetometer.

In the H axis, where the more sensitive SQUID is installed, the data is contaminated with its response to a 5 mHz thermal oscillation in the LN_2 bath. Envisioned solutions to mitigate the oscillations range from keeping the LN_2 dewar 100% full all the time to keeping the system below atmospheric pressure to stabilize the temperature well below the critical temperature of the SQUIDs. Also, alternative dewars with extended holding time may be available, but their thermo-acoustic properties need be investigated. However, we have shown that calculating the coherence is useful not only to suppress the man-made noise, but also the SQUID thermal oscillations.

The data and solution presented indicate that an unshielded HTS SQUID magnetometer could be generally useful as a space weather instrument for detecting low-amplitude Pc and Pi pulsations. Given its high resolution, an improvement in forecasting of geomagnetic storms should also be possible.

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